GEOLOGY, PROSPECTING AND EXPLORATION OF MINERAL DEPOSITS

Original article
https://doi.org/10.21285/2686-9993-2022-45-4-324-344

Applications of high-resolution seismic frequency and phase attribute analysis techniques

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Abstract. Seismic prospecting for oil and gas exploration and development is limited by seismic data resolution. Improving the accuracy of quantitative interpretation of seismic data in thin layers, thereby identifying effective reservoirs and delineating favorable areas, can be a key factor for successful exploration and development. Historically, the limit of seismic resolution is usually assumed to be about 1/4 wavelength of the dominant frequency of the data in the formation of interest. Constrained seismic reflectivity inversion can resolve thinner layers than this assumed limit. This leads to a series of high-resolution quantitative interpretation methods and techniques have been developed. Case studies in carbonates, clastic, and unconventional reservoirs indicate that the application of quantitative interpretation techniques such as high-resolution seismic frequency and phase attribute analysis can resolve and allow/or allow quantitative estimation of rock and fluid properties in such seismically thin layers. Band recovery using high resolution seismic processing technology can greatly improve the ability to recognize geological details such as thin layers, faults, and karst caves. Multiscale fault detection technology can effectively detect small-scale faults in addition to more readily recognized large-scale faults. Based on traditional seismic amplitude information, high-resolution spectral decomposition and phase decomposition technology expands seismic attribute analysis to the frequency and phase dimensions, boosting the interpretable geological information content of the seismic data including subsurface geological characteristics and hydrocarbon potential and thereby improving the reliability of seismic interpretation. These technologies, based on high-resolution quantitative interpretation techniques, make the identification of effective reservoirs more efficient and accurate.

Keywords: high-resolution seismic spectral decomposition, phase decomposition, band recovery high resolution enhancement, multi-scale fault detection

Acknowledgements: The editorial board thanks the editors of the Earth Science Frontiers journal for providing the material under the agreement between the editors of the Irkutsk National Research Technical University (Irkutsk, Russia) and the China University of GeoSciences (Beijing, China) on the exchange of open access scientific articles.

For citation: Jiang Renqi, Castagna J. P., Wu Jian. Applications of high-resolution seismic frequency and phase attribute analysis techniques. *Nauki o Zemle i nedropol'zovanie = Earth sciences and subsoil use.* 2022;45(4):324-344. https://doi.org/10.21285/2686-9993-2022-45-4-324-344.

ГЕОЛОГИЯ, ПОИСКИ И РАЗВЕДКА МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Научная статья
УДК 550.8.05

Использование сейсмической частоты высокого разрешения и фазовых атрибутов как приемов анализа

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Резюме. Сейсмические исследования для разведки и разработки месторождений нефти и газа ограничены разрешающей способностью сейсмических данных. В данном случае ключевым фактором успешной разведки и разработки месторождений может стать повышение точности количественной интерпретации сейсмических данных в маломощных пластах, позволяющее выявить эффективные резервуары и обозначить благоприятные участки. Исторически сложилось так, что предел сейсмического разрешения обычно считается равным примерно 1/4 длины волны доминирующей частоты данных в интересующем пласте. С помощью ограниченной инверсии сейсмической отражательной способности можно распознать более тонкие слои, чем этот предполагаемый предел, что привело к разработке ряда методов и приемов высокоразрешающей количественной интерпретации. Предметные исследования карбонатных, обломочных и нетрадиционных залежей показывают, что применение методов количественной интерпретации, таких как сейсмический высокоразрешающий частотный анализ и анализ фазовых атрибутов, позволяет распознать и разрешить количественную оценку свойств горных пород и флюидов в таких сейсмически тонких слоях. Восстановление диапазона частот с использованием технологии высокоразрешающей обработки сейсмических данных может значительно улучшить способность распознавания таких геологических деталей, как тонкие слои, разломы и карстовые пещеры. Технология многомасштабного обнаружения разломов может эффективно выявлять мелкие разломы наряду с более легко распознаваемыми крупномасштабными разрывами. Технология высокоразрешающего спектрального разложения и фазового разложения, основанная на традиционной информации о сейсмической амплитуде, расширяет сейсмический атрибутный анализ до размера частоты и фазы, чем расширяет содержание интерпретируемой геологической информации о сейсмических данных, включая геологические характеристики и потенциал углеводородов, и тем самым повышает надежность сейсмической интерпретации. Эти технологии, основанные на методах количественной интерпретации с высоким разрешением, позволяют более эффективно и точно обнаруживать продуктивные коллекторы.

Ключевые слова: высокоразрешающее сейсмическое спектральное разложение, фазовое разложение, восстанавливающее диапазон частот усиление высокого разрешения, многомасштабное обнаружение разломов

Благодарности: Редколлегия благодарит редакцию журнала Earth Science Frontiers за предоставление материала в рамках соглашения между редакциями Иркутского национального исследовательского технического университета (г. Иркутск, Россия) и Китайского университета геологических наук (г. Пекин, Китай) об обмене научными статьями открытого доступа.

Для цитирования: Цзян Жэньци, Кастанья Дж. П., Цзянь У. Использование сейсмической частоты высокого разрешения и фазовых атрибутов как приемов анализа // Науки о Земле и недропользование. 2022. Т. 45. № 4. С. 324–344. https://doi.org/10.21285/2686-9993-2022-45-4-324-344.

Introduction

Quantitative seismic interpretation utilizes the characteristics of reflected seismic waves to infer geological features and rock/fluid properties of subsurface strata [1–3]. In the field of petroleum exploration and development, two issues are particularly important: first, the resolution of seismic data does not always meet exploration and development needs; second, the incompleteness and complexity of information in seismic signals lead to a strong ambiguity of scales of geological interpretation based on seismic attributes.

Resolution of seismic data. As exploration and development of petroleum fields and basins mature and has entered the stage of detailed and refined exploration and development, especially after the oil and gas fields have entered the middle and late stages of development, the requirements for the vertical identification, delineation and exploitation of stratigraphic units are increasing, the need to make geological inferences for seismically thin reservoirs or flow units (individual sand formations, reefs, highly permeable carbonate formations, etc.) has increased. Many individual sand formations around 10 m or even thinner in China have become the main reservoir interval for development. However, due to the 1/4 wavelength limitation of conventional seismic data it is typical to be able to resolves only layers of several tens of meters, which may not meet the requirements of oil and gas field production.

There are two commons to improve the vertical resolution of seismic data: one is to perform high-resolution acquisition using equipment and geometries to maximize high frequency signal, and the other is to digitally process the seismic data in such a way as to maximize the breadth of the spectral bandwidth. High-resolution seismic acquisition not only increases the cost and time greatly, but also suffers from physical limitations that may prevent the acquisition of the required frequency content. Therefore, the development of theories and methods to improve the resolution processing of conventional seismic data has become a subject of research among geophysicists [4, 5].

A variety of methods to improve seismic resolution have been, including various processing of seismic signals and compensation of high-frequency signals using well data [e.g., 6]. However, there is an obvious problem with all these methods at present, namely the fidelity of the processing results. Does the extra reflected wave after processing have a geological meaning? Does it correspond to the wave impedance contrast of the stratum interface? Are the vertical and lateral variations of seismic reflections a true indication of the stratigraphy? If the processing results in distortion of the seismic signal, it will not only not help geological research, but also lead to wrong interpretation and judgment, and reduce the success rate of drilling. Therefore, how to improve the resolution with high fidelity and thus truly enhance the thin layer identification is the biggest challenge to improve seismic resolution processing technology.

In a blocky earth impedance structure, the simple assumption of sparsity of reflection coefficient pairs at layer boundaries can be used to extend the seismic bandwidth and improve seismic resolution [4, 5] based on the characteristics of the reflection coefficient spectrum of stratigraphic reflection coefficient pairs with periodic oscillations in the frequency domain. When the assumption of a sparse number of layers realistically captures the true reflectivity series, this can significantly improve the resolution of seismic data with good fidelity, and has been verified in numerous oil and gas production applications [e.g., 4, 5, 7].

Non-uniqueness of seismic reflection wave properties. Even with perfect noise-free data, an infinite number of earth models can result in the same band-limited reflection seismogram. The use of various attributes of seismic reflection waves to study the geological characteristics of subsurface reservoirs has been the main content of geological research in oil and gas fields. However, the complexity of the subsurface geological situation leads to numerous factors affecting the seismic attributes, and the seismic data acquisition and processing also affect the attributes of seismic reflection waves, so there are indeed many solutions to the inversion problem and uncertainty of inverted impedance has been a great factor limiting the work of predicting reservoir characteristics using seismic attribute parameters, especially below seismic tuning. It is the goal of many geophysicists to mine seismic attributes from seismic reflection waves that are less poly synthetic and more closely and directly related to the geological characteristics of reservoirs, to carry out more in-depth, specific and accurate prediction of subsurface oil reservoirs. Practical applications show that increasing the dimensionality of seismic attributes is a very effective method. Ultimately, prior information is required to constrain the possible solutions, and how this information is employed has a great influence on the resolution of the inversion result. As discussed in [5, 7], there are a few common means of employing a priori information (1) using a starting earth impedance model, (2) assuming a sparse number of reflection-coefficients, and (3) qualifying the inversion objective function in terms of deviation from prior assumptions such as rock physics relationships etc. Method (1) necessarily biases the inversion result greatly towards pre-conceived

Seismic reflections have three basic attributes: amplitude, frequency, and phase. Spectral decomposition provides the time-localized frequency dependence of amplitude and phase. If we decompose the seismic reflection waves according to different frequencies or phases, analyze the distribution characteristics and differences of reflection energy (amplitude) at different frequencies or phases, and find out the "characteristic frequency" or "characteristic phase", it is possible to reduce the multiplicity of seismic properties. This reduction can result in improved visualization of geological features.

The research and prediction of reservoir properties through the distribution characteristics and rules of seismic wave propagation in the frequency and phase domains increases the dimensionality of the analysis of seismic attributes. This does not increase the information content of the seismic data, but rather subsets it in different ways, to make specific information more apparent and interpretable.

To analyze the reflected energy of seismic reflection waves in different "domains" (frequency or phase domains) from a multidimensional perspective, and to identify the characteristic frequencies or phases of different geological units, special algorithms are needed to decompose the seismic reflection wave signals with high resolution and high fidelity, so that the information contained in the original seismic signals can be revealed. Constrained-least squares spectral analysis [8] and subsequent phase decomposition [9] makes the multidimensional information content more interpretable in terms of rock and fluid characteristics.

Technical approach

Spectrum recovery technology to improve resolution. Conventional understanding of seismic resolution is largely based on the Widess model [10] and deconvolution theory based on the Fourier convolution theorem. Over 60 years ago, Widess [10] calculated synthetic seismograms for a thinning wedge layer with exactly equal and opposite reflection coefficients encased in two-half spaces. Generalizations from this model are unfortunately highly misleading, as it is a unique case where the even part of the reflectivity series is exactly zero. For the more general case of a non-zero even part, as the layer thins, the even part becomes more significant while the odd part tends to cancel. According to the Widess model, below 1/8th of a wavelength (λ), for all practical purposes, only the amplitude of the composite waveform changes with thickness following a tuning curve, but the peak/trough time separation, and therefore the dominant frequency of the reflection is almost invariant. More specifically, the dominant frequency for a Widess thin-layer approaches that of the derivative of the seismic wavelet as thickness goes to zero. This means that it is impossible to determine whether an amplitude change of a thin layer well below tuning is due to a time-thickness change for the layer or a change in layer impedance. In inversion for a thin layer with exactly equal and opposite reflection coefficients, layer thickness and impedance will trade off and in the presence of even a small amount of noise inversion will be unstable. Many conventional inversion algorithms thus are designed to not even attempt to invert for very thin layers. Again, as a practical matter, in the presence of noise, and as side-lobe interference effects may further confuse the signal, the actual limit of seismic resolution is often considered to be λ/4 [3, 10].

But Tirado [3] in 2004, modeling a more realistic wedge model derived from a sonic log, found that, contrary to the Widess model, the dominant frequency decreased systematically as the layer thickness thinned below λ/8; when the layer thickness is less than a certain thickness (tuning frequency turning point), the main frequency starts to decrease and coincides with the main frequency of the wavelet (rather than the derivative of the main frequency of the wavelet) at a layer thickness of 0. This conclusion is just the opposite of Widess's predicted conclusion for thin layers.

Puryear and Castagna [4] argued that in practice, the reflection coefficients at the upper and lower stratigraphic interfaces are not typically the same as in the Widess model, but more of a laminar distribution with different impedance of the upper and lower media, which can be decomposed into an “odd” reflection coefficient pair and an “even” reflection coefficient pair (Fig. 1). The Widess model is a special, which means that the resolution limit of the Widess model is not limited as long as the “even” reflection coefficient pair is not zero. As the variation in dominant frequency is a continuous quantity, this means that layer thicknesses that are even smaller than the sampling interval of the seismic signal can theoretically be predicted.

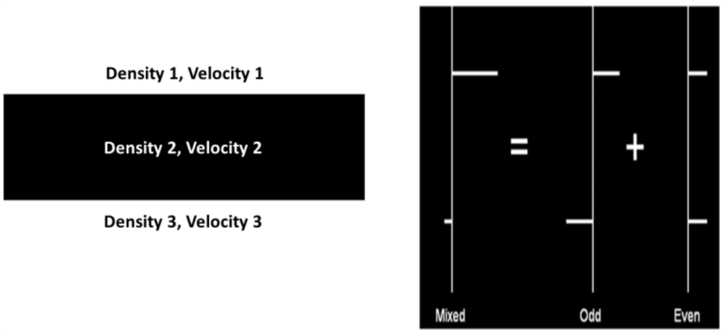

Fig. 1. Strata model and its reflectivity (modified after [4])
Рис. 1. Модель пластов и ее отражательная способность (согласно источнику [4] с изменениями)

According to odd/even analysis, the variation characteristics of peak amplitude and frequency of odd and even reflection coefficient pairs with layer thickness are represented separately (Fig. 2). The total reflection response is a combination of odd and even responses. Note that below *λ*/8, for this particular case there is a 5 Hz change in peak frequency at thickness for which the Widess model (odd part) suggests that the waveform frequency will not change appreciably. As an even reflection coefficient pair is, by definition, zero-phase, one can see that if there is any even part to the reflectivity series, the thin layer response should go to zero phase as the thickness approaches zero, rather than 90° phase as predicted by the Widess model.

The spectral recovery resolution enhancement technique uses reflection coefficient pairs, rather than a single reflection-coefficients, to represent stratigraphic units, which can achieve improved detail identification and lateral stability. Sparse-spike inversion finds the reflection coefficient series that minimizes the sum of the reflection coefficient magnitudes while also reproducing the data. This has the effect of minimizing the time thickness of odd reflection coefficient pairs, as the smallest pair will occur at the greatest layer thickness. Parameterizing the inversion differently [e.g., 7] one can minimize, for example, the number of reflection coefficient pairs summing to form the reflectivity series. We refer to this approach as sparse layer inversion. Note that with this approach, there is no built-in bias against thin layers in the inversion objective function. Unlike traditional sparse spike inversion, sparse layer inversion uses the sparsity of layers as a constraint, unlike sparse spike inversion which is sensitive only to thick strata and ignores thin layers. According to the generalized reflection coefficient model, both the odd and even parts of a stratigraphic reflection coefficient decomposition can be considered as a pair of reflection coefficients (spikes) of equal magnitude at top and base of a layer. When sinusoidal of different frequencies and such a pair of spikes are convolved, some frequencies constructively interfere while others destructively interfere, and periodic peaks and troughs appear in the frequency domain (Fig. 3). The periodicity in the frequency domain (quefrency) is only related to the thickness of the reflection coefficient pair. Based on the fact that the distance between the peak and the trough on the frequency spectrum is a deterministic function of the thickness of the formation, a new algorithm for reflection coefficient inversion in the frequency domain using a summation of constant periodic values can be derived. The coefficients of the real part of the complex spectrum are exactly equal to the even part of the generic reflection coefficient model, and the coefficients of the imaginary part are equal to the odd part of the reflection coefficient model. Using this property, a simultaneous coupling of the odd and even parts of the thin-layer reflection record can be optimally fitted to obtain the thin-layer thickness and the odd and even reflection coefficients. For the multilayer case, a matrix equation system consisting of several sequences of thin-layer even part, odd part, and thickness is formed, and the spectrum of the stratigraphic reflection coefficients can be obtained by inversion solution of the simultaneous search-and-fit [5, 7, 8].

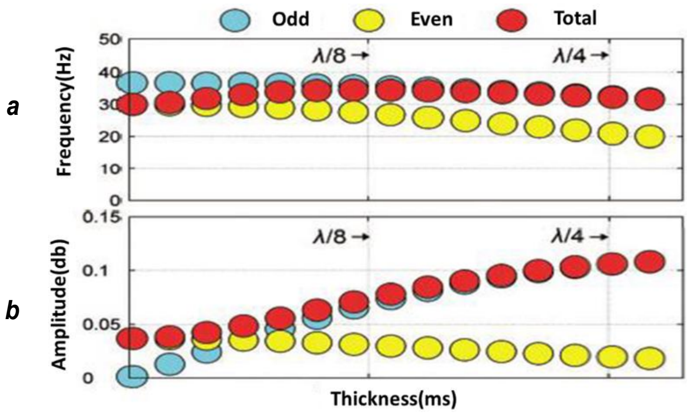

Fig. 2. Peak frequency and peak amplitude vs. thickness variation (modified after [4])
Рис. 2. Зависимость пиковой частоты и пиковой амплитуды от изменения толщины (согласно источнику [4] с изменениями)

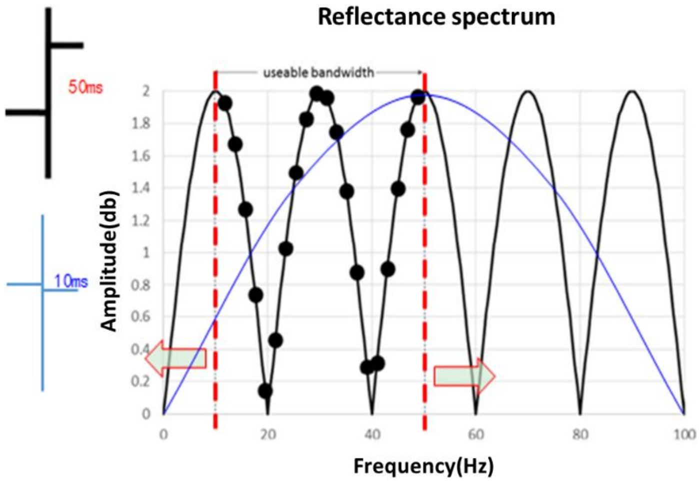

Fig. 3. Schema of band recovery high resolution processing (modified after [5])
Рис. 3. Схема высокоразрешающей обработки восстановления диапазона частот (согласно источнику [5] с изменениями)

Traditional spectral analysis based on the Fourier Transform suffers loss of temporal and frequency resolution due to windowing the data. In essence, the Fourier Transform yields the spectrum of the windowed data. Similarly, resolution of Wavelet Transform spectral analysis is controlled by the resolution of the analyzing wavelets and suffers from the Heisenberg Uncertainty Principle which states that the product of temporal and frequency resolution for any given wavelet dictionary is a constant; one must always pay the price of reduced resolution in one domain, when attempting to increase resolution in the other domain. A sparse wavelet approach can be applied to the problem of spectral decomposition and improve frequency resolution without degrading time resolution [6]. The result is an estimate of the spectrum of the data within the window, rather than the spectrum of the windowed data. This provides high-resolution spectral decomposition which improves sparse-layer inversion and thus spectrum recovery; recovering and using the high-frequency information of the data from the original seismic data, thereby making an overcoming the defects of the Fourier transform, so that the seismic resolution after sparse-layer inversion breaks through the seismic resolution of the traditional Widess model. Unlike deconvolution, which at any frequency boosts the noise the same amount as the signal at the frequency, this approach benefits from the S/N ratio of the main band of the seismic data, and thereby boosts the signal more than the noise on the spectral tail at high frequency. The seismic resolution can reach 1/8 to 1/16 of the original seismic signal wavelength [4]. Its resolution, fidelity and reliability are significantly advanced and improved compared with the previous techniques, and it has unique advantages for the interpretation and identification of thin reservoirs.

High resolution spectrum decomposition technology. Due to the sensitivity of amplitude variation with frequency, different geological objects have different response characteristics in different frequency bands. More detail, more definite, and more localized reflection attributes and identification can be obtained in different frequency bands. Therefore, through spectrum decomposition, the frequencies that best convey the information of interest can be preferentially selected, and the characteristics of reservoirs can be interpreted and studied more clearly and accurately. In the past two decades, the spectrum decomposition technique has been widely used in fine geological interpretation, however, traditional seismic spectrum decomposition has limited resolution in either the time or frequency domains [3, 8], and the temporal resolution and frequency resolution cannot be maximized at the same time, so a method optimized for seismic interpretation purposes is needed.

This spectral decomposition technique is implemented by the constrained least squares complex spectral decomposition (CLSSA) method [8]. Compared to other methods (Fig. 4), the CLSSA method is a high-resolution spectral decomposition method with high temporal and frequency resolution at the same time. Performed as an

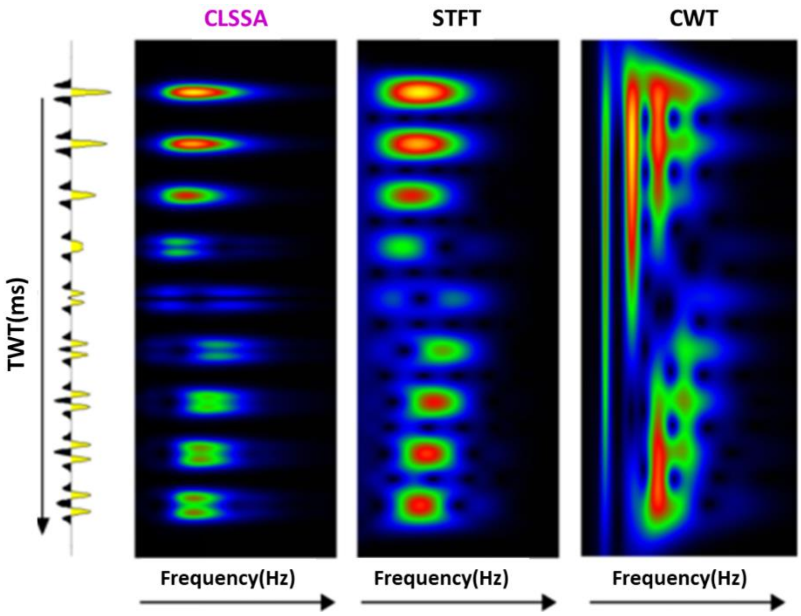

Fig. 4. CLSSA (Constrained Least Squares Complex Spectral Decomposition), STFT (Short-time Fourier Transform) and CWT (Continuous Wavelet Transform) spectral decomposition of a seismic trace (modified after [8])
Рис. 4. Спектральное разложение сейсмической трассы CLSSA (комплексное спектральное разложение методом наименьших квадратов с ограничениями), STFT (кратковременное преобразование Фурье) и CWT (непрерывное вейвлет-преобразование) (согласно источнику [8] с изменениями)

inversion process, it is possible to fit the broadband output results to the input data as a superposition of wavelet dictionary atoms. This process uses temporally and spatially varying wavelets, which is important for large data sets with spatial wavelet variations, so that the output spectrum is stable (in a statistical sense) in time and space.

Spectral decomposition using the least squares method (CLSSA) has unique advantages. For a given time window, it reduces the temporal and spectral smoothing effect of the window in contrast to the discrete Fourier transform. The reduced spectral smoothing ensures better identification of the reflection spectral properties within the short-time window. The temporal resolution is equal to the resolution of the data, rather than that of the window. The degree of frequency resolution improvement of the CLSSA method relative to the short-time Fourier transform increases with the reduction of the time window length. In addition, the CLSSA method substantially improves the temporal resolution, especially at low frequencies, compared to the continuous wavelet transform which utilizes long low-frequency wavelets. Therefore, the least-squares method for spectral decomposition is superior to both the short-time Fourier transform and the continuous subwave transform.

The CLSSA output has the temporal resolution of the seismic data itself, without being limited by the temporal resolution of the window or the analyzed wavelets, while maintaining the necessary frequency resolution. This technique enables a variety of previously unattainable application ideas, including finer stratigraphic and structural imaging, detection and quantification of fractures and faults, expansion of the bandwidth of seismic data, and more accurate reservoir prediction or direct detection of hydrocarbons.

Phase decomposition technique. Phase decomposition [9] is a new and unique application. Seismic impedance anomalies caused by pore fluids as well as lithological variations are often difficult to observe using conventional seismic profiles as they are masked by other lithological impedance variations unrelated to hydrocarbons or reservoir rock. However, impedance variations in seismically thin layers can result in more distinctive amplitude variations in the different phase components of the seismic response. By decomposing the seismic traces into different phase components while suppressing the unwanted phase components, subtle features can sometimes be more clearly identified. For example, a weak seismic reflection amplitude anomaly response caused by hydrocarbon changes, lithology changes, or sedimentary unit changes may show significant amplitude on a desired phase component. Using this technique, a completely different but more accurate map of the extent of the thin reservoir and its location can sometimes be generated.

Different from the instantaneous phase attribute which conveys no reflection strength information and phase rotation which does not change the amplitude envelope of events, seismic phase decomposition is a new technique to study subsurface geological targets by expanding seismic trace amplitudes in the phase domain on the basis of high-resolution time-frequency analysis to obtain the energy distribution of seismic reflections related to phase only, and then analyze the energy changes in the phase domain for different geological features and differences in lithology and physical properties.

By spectral decomposition, seismic trace amplitude can be decomposed into a three-dimensional function of amplitude versus frequency and phase. A seismic trace is a one-dimensional function of amplitude with time $S(t)$. The amplitude spectrum is a two-dimensional function $A(f, t)$ of amplitude with time and frequency, and the phase spectrum is a two-dimensional function $\theta(f, t)$ of phase with time and frequency. If we form the amplitude spectrum and phase spectrum as a function $A(f, t)*\cos[\theta(f, t)]$, then the two-dimensional function representing the reflection amplitude as a function of phase and time can be obtained by the following equation:

$$S'(\theta,t) = \int_{f_1}^{f_2} A(f,t)\cos\theta(f,t)df,$$

where f_1 and f_2 are the start and cutoff frequencies of a selected frequency band. We refer to this function as the phase channel set. Any desired phase component in the specified frequency band is extracted by the following equation:

$$S'(t) = \int_{\theta_1}^{\theta_2} S'(\theta,t)\,d\theta,$$

where θ_1 and θ_2 are the onset and cutoff phases of the phase interval. In this way, the seismic reflection homogeneous axis with specific spectral characteristics can be suppressed or enhanced. The process of decomposing seismic traces into a two-dimensional function of amplitude with time and phase is called phase decomposition (Fig. 5).

The change in amplitude for a specific phase with time is called the phase component. It is possible to amplify the seismic reflection energy changes caused by small impedance changes in strata below the tuned thickness, making specific geological features more easily detectable. Any pair of reflection coefficients can be expressed as a sum of the odd and even components [3, 11, 12]. Even-component reflection coefficients have the same magnitude and sign, and odd-component reflection coefficients have the same magnitude and opposite sign [3, 12]. In an isolated thin layer, the change in impedance changes the odd component of the reflectivity and thus the phase

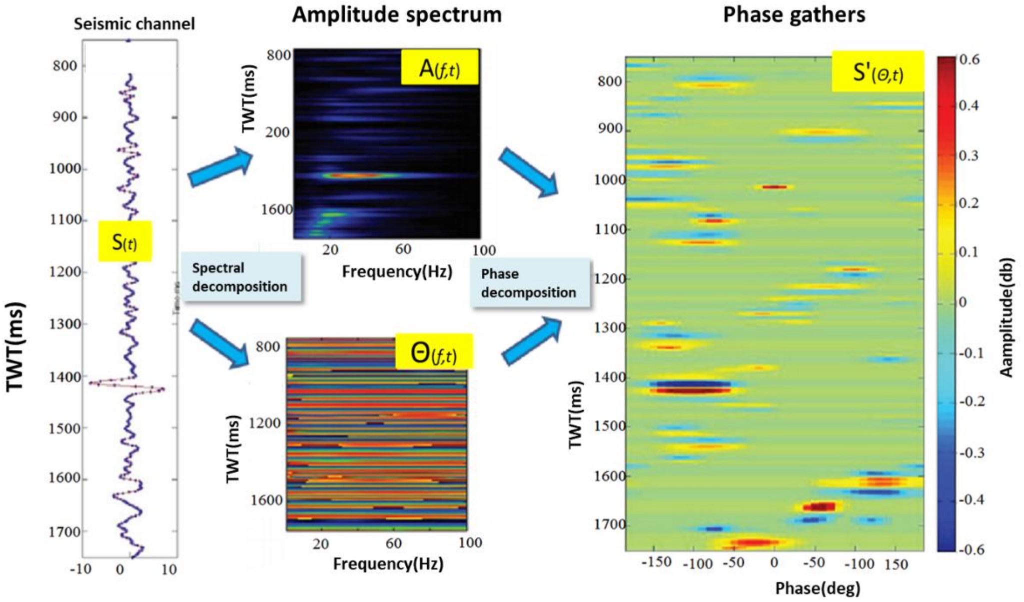

Fig. 5. Schema of phase decomposition of a seismic trace
Рис. 5. Схема фазового разложения сейсмической трассы

of the local reflectivity, while the even component remains almost constant. When the phase of seismic data is filtered according to the above method, the odd component of the phase may exhibit a stronger apparent amplitude anomaly at the location of the original amplitude. In particular, in the case of low-impedance thin-layered gas-bearing sandstones (bright spots), the amplitude anomalies corresponding to the gas saturation will appear in the -90° phase component if the seismic wavelet is zero phase. Therefore, the reconstruction of specific phase bands of the superimposed data can be used as a means of hydrocarbon detection or physical prediction of seismic thin layers.

As an example, Figure 6, *a* shows the top and bottom interface reflection coefficient pairs of a formation without oil and gas, and the seismic response, with 0° and -90° phase components. Figure 6, *b* shows that the top and bottom interface reflection coefficient pairs of the formation are slightly changed after containing oil and gas, with the top interface reflection coefficient becoming smaller and the bottom interface reflection coefficient becoming larger. However, because the impedance difference is small, the seismic response is almost the same as that without oil and gas. After the phase decomposition, it can be found that the seismic response of the 0° phase component is almost the same as that of the formation without oil and gas; while the seismic response of the -90° phase component is significantly amplified.

When the seismic impedance anomalies caused by pore fluid and lithological changes are not obvious, the energy distribution on different phase components may be significantly different. The phase decomposition technique originally decomposes each seismic trace into different phase components, and by analyzing the seismic reflection energy on different phase components, some subtle anomalous responses caused by pore fluid (containing oil and gas) changes and lithology changes can possibly be identified. The phase decomposition technique can decompose and reconstruct the seismic traces to extract the most sensitive part of the seismic signal for oil and gas response, so that the weak anomalies caused by reservoir physical changes or oil and gas-bearing can be more apparent and improve the accuracy of oil and gas prediction.

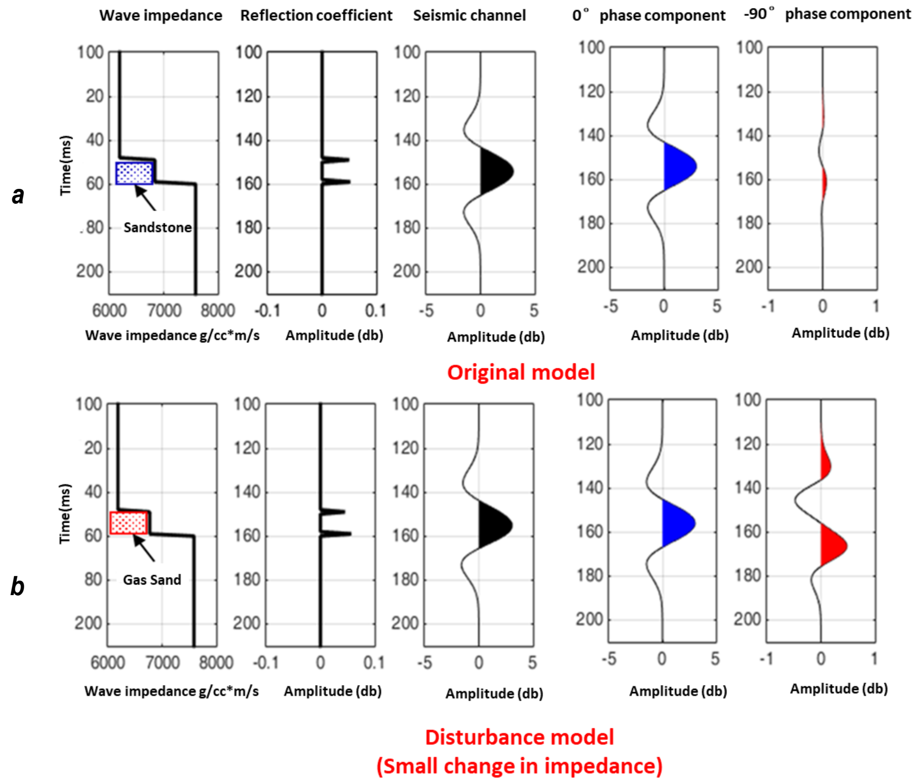

Fig. 6. Schema of phase decomposition of a seismic trace:
a – original model, b – disturbance model
Рис. 6. Схема фазового разложения сейсмической трассы:
a – исходная модель, b – модель отклонений

Multi-scale fault detection (FaultDetect) technology. The accurate interpretation of fault systems, especially the identification and interpretation of complex fault systems, hidden faults and small faults, etc., has been a difficult problem in geological studies of oil and gas reservoirs. Currently, fault detection techniques commonly use geometric attributes such as coherence, dip, azimuth and curvature [13–17]. Since the coherence technique was proposed, it has been a hot topic in interpretation techniques and has been very helpful for fault interpretation [18–20].

However, these common fault detection techniques are used to determine the distribution of the spatial continuity of seismic attributes by calculating the similarity of adjacent seismic traces. The calculation results are all affected by the calculation time window and dominant frequency of the seismic data, which makes the calculated fault location deviate from the actual fault location in the plane, resulting in the detected fault location being somewhat erroneous on a time slice.

Large-scale faults with large fault displacement can be identified using conventional techniques such as coherence and curvature attributes on conventional seismic data, but high-angle faults or tiny faults with insignificant displacement are difficult to be accurately identified and described on conventional seismic profiles [21, 23]. New fault detection and processing techniques are needed to accurately identify the location of breakpoints of tiny faults, so that the spatial continuity and extension of the section can be displayed more clearly and accurately.

In the frequency domain, the seismic response of different geological features in the subsurface has the most obvious response at different characteristic frequencies. It is the trend of seismic exploration technology development to extend the traditional seismic imaging and interpretation work in the time domain to the frequency domain.

Similar to the principle of focused imaging, there are significant differences in the accuracy and clarity of different scales of faults reflected in different frequency bands of seismic signals [23–27]. In imaging and interpreting the temporal thickness and geological discontinuities of 3D seismic data, the corresponding most sensitive attributes of seismic response imaging in different frequency bands can be analyzed in the frequency domain by high-resolution time-frequency analysis, and the faults can be finely imaged by the changes of seismic information in different frequency bands. The seismic phase discontinuity caused by the vertical displacement of a fault is most obvious when the seismic record time change from traces on either side of the fault is equal to a half-period of the dominant frequency of the seismic data. As a corollary, the phase discontinuity caused by a fault of any throw, is maximized at the spectral decomposition frequency corresponding to a vertical displacement in seismic record time of a half-period of that frequency. In this way, high resolution spectral and phase decomposition can be used to find the frequency at which maximum phase and amplitude discontinuity will occur for any fault. Various seismic discontinuity measures as a function of frequency can be thus combined to form an optimized discontinuity attribute.

Specific implementation process: First, the 3D seismic data set is decomposed into a high-resolution time-localized complex spectrum to generate a series of single-frequency data sets, and the amplitude and phase data sets of the corresponding multiple frequencies are obtained. Then, edge enhancement is performed on the amplitude and phase data sets of different frequencies, and the fault detection attribute data sets reflecting different scales are obtained by identifying various preferred discontinuity attributes such as waveform, amplitude and phase at different frequencies. These data are then combined using adaptive principal component analysis to form the final comprehensive fault detection attribute. This is readily followed by automatic fault tracking and identification.

The frequency-domain multiscale fault detection (FaultDetect) technology has the following features: (1) Starting from the frequency domain, it can realize the identification of weak seismic response discontinuities, provide more accurate fracture information, and improve the interpretability of the fault grid system; (2) The identification results have a very high vertical resolution, and the fault location and fault displacement can be accurately carved in 3D. The frequency-domain multidimensional multiscale fault detection technique is particularly useful for strike slip faults with small vertical displacement, which are difficult to be recognized by human eyes. Geological variations across the fault, however, may produce subtle seismic character changes which are detected by this algorithm.

The biggest technical advantage of frequency-domain multiscale fault detection (FaultDetect) technology is that it adds a variety of discontinuity attribute information in the frequency domain, so that the discontinuity in seismic reflection can be reflected and described more accurately and clearly. It can map the complex multiscale fault network and produces geological meaningful vertical and lateral slices through the 3D fault attribute volume. It consequently has higher resolution and reliability than traditional fault identification methods such as coherence and curvature, and is thus a true three-dimensional fault detection technology. Compared with other fault detection methods, the frequency domain fracture detection technique detects fault breaks with higher accuracy and has stronger recognition ability for shear faults, high-angle faults and micro faults (Fig. 7).

Application examples

Application examples in the Tarim Basin. The Tarim Basin is a hydrocarbon-rich basin with many types of hydrocarbon reservoirs. Among them, carbonate reservoirs are mainly of cave and fracture types; how to accurately describe the caved and fractured reservoir system and predict the hydrocarbon-bearing formations is the key for accurate exploration and development. In contrast, clastic reservoirs are characterized by large changes in reservoir properties, and it is a major challenge to conduct detail reservoir studies for oil and gas-bearing reservoirs. A number of studies have been carried out in the Tarim Basin using the above-mentioned new techniques, all of which have achieved good results.

The reservoir unit in the target area of marine carbonate in Tarim Basin is dominated by the cave system controlled by the fault and fracture system, especially as caverns often form highly productive oil and gas reservoirs. However, due to the complex surface conditions, coupled with the large burial depth of the target layer and serious absorption and attenuation, it leads to the low original dominant frequency of the target layer of seismic data, weak high-frequency signals, and inconspicuous imaging of caves and small fractures, resulting in certain difficulties in the accurate identification and interpretation of cave systems. Therefore, it is necessary to improve the resolution of seismic data through reliable and effective means to obtain a high-resolution seismic dataset and improve the recognition and interpretation capability of seismic data in faulted systems and karst (cave) type reservoirs.

Firstly, in response to the problems of low resolution of the original seismic data, unclear breakpoints on the profile, and difficult interpretation of the faults (Fig. 8, *a*), the resolution enhancement processing was carried out by using the spectrum

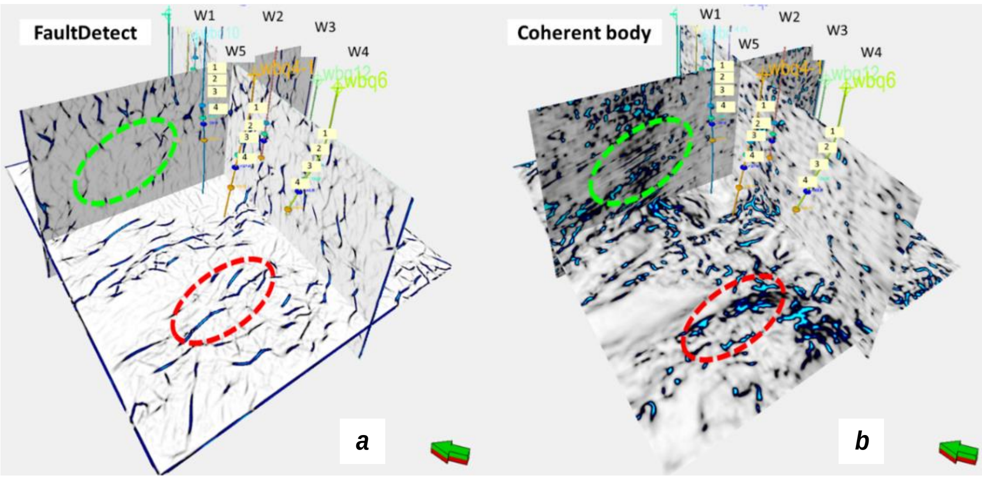

Fig. 7. 3D views of Faultdetect and Coherence volumes:
a – multi-scale fracture detection body 3D result map; b – coherent body fracture detection 3D result map
Рис. 7. Трехмерные изображения томов Faultdetect и Coherence:
а – многомасштабная 3D-карта результатов обнаружения разломов тела; b – трехмерная карта результатов когерентного обнаружения разломов тела

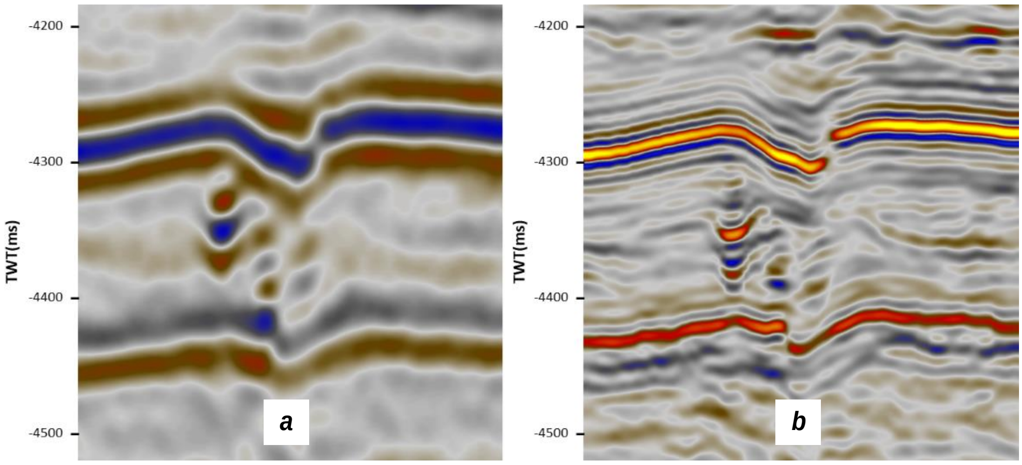

Fig. 8. Seismic sections before and after high resolution processing:
a – conventional seismic profile; b – seismic profile after improved resolution processing
Рис. 8. Сейсмические участки до и после высокоразрешающей обработки:
a – условный сейсмический профиль; b – сейсмический профиль после улучшенной высокоразрешающей обработки

recovery to improve the seismic resolution processing technique, and the main frequency of the processed seismic data was greatly improved, and the bandwidth became wider. At the same time, the fault boundary information was highlighted and the ability to identify faults was effectively enhanced (Fig. 8, *b*).

Due to the low resolution of the original seismic data, the imaging of the caves on the profile is not clear and difficult to interpret the display. After improving the resolution processing, the main frequency of seismic data is increased and the bandwidth becomes wider. At the same time, the boundary of the cave is more accurately imaged, the recognition ability is obviously enhanced, and the multiphase cave is well reflected.

The oil and gas reservoir in an area of Tarim Basin is a cave type reservoir, and the spatial distribution of the cave reservoir is mainly controlled by faults, and the accurate identification and interpretation of the fault system is the key to the design of the exploration and development plan of the reservoir. However, due to the multi-period tectonic movements, the fault system is very complex, and multiple phases and multiple sets of faults are developed, making the accurate interpretation of the fault system one of the main challenges in the geological research of the area.

The 3D seismic data in this area have undergone several re-processing and interpretations, but due to the limitations of previous research methods, they basically can only satisfy the interpretation of the main fault, and it is difficult to meet the requirements of interpretation of small micro-faults within the main fault and fine description of faults [21]. To address this problem, the seismic data in the area were processed and systematically interpreted using frequency-domain multiscale fault detection. Comparing the coherent and frequency-domain multiscale fault detection data profiles (Fig. 9), the coherence dataset contains some footprints and linear interference along the layer affecting the fault identification, while the frequency-domain multiscale fault detection dataset strengthens the discontinuity of seismic data while removing footprints and linear interference along the layer, and the predicted results have clear fault plans, good continuity, and good matching relationship with the caved reservoir.

At the same time, the multiscale fault detection with a variety of sensitive seismic attributes in the frequency and phase domains can provide a clearer picture of the common “fault-solution” system in the west part. As shown in Fig. 10, the color in the figure represents the caved reservoir, and the black color represents the development and distribution of different scale of faults.

Some carbonate caved type oil and gas reservoir development areas have been discovered in Tarim Basin, but drilled wells have found that the oil and gas properties of different cave bodies in the same area vary greatly, and there are both highly productive oil and gas producing wells and water only producing wells. How to use seismic data to identify oil-bearing cave and

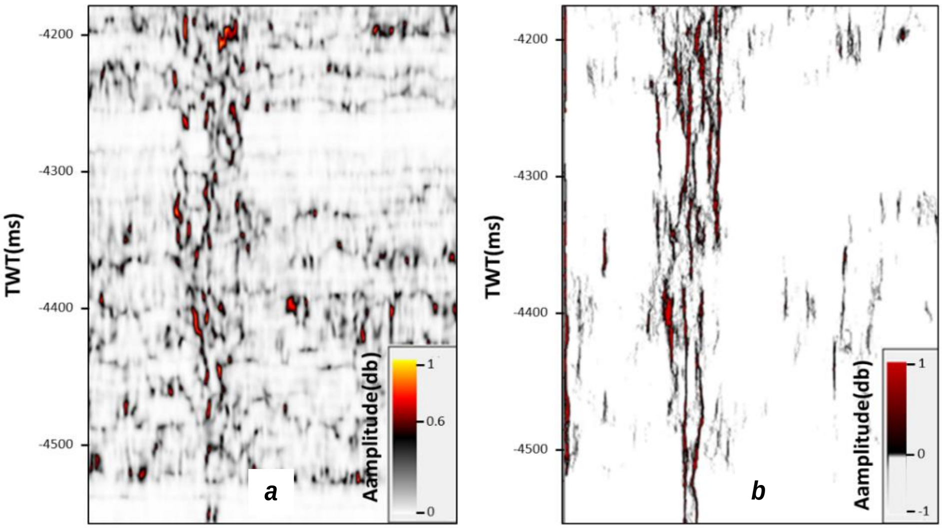

Fig. 9. Sections of Coherence and FaultDetect:
a – coherent body profile; b – multi-scale fracture detection body profile
Рис. 9. Участки в Coherence и FaultDetect:
a – целостный профиль тела; b – многомасштабный профиль тела для обнаружения разломов

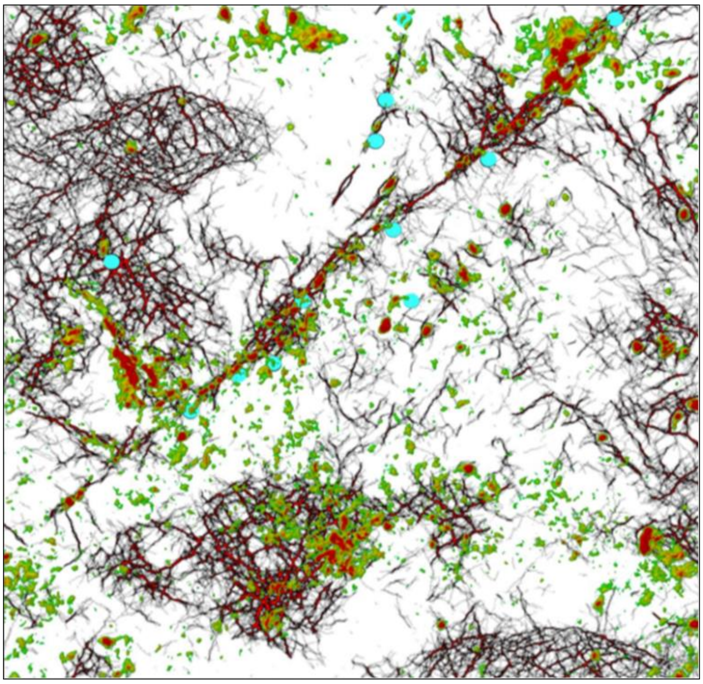

Fig. 10. Slice of Faultdetect overlay on Amplitude attribute (delineate caves)
Рис. 10. Фрагмент наложения Faultdetect на атрибут Amplitude (обозначение полостей)

improve the exploration success rate is one of the main tasks of geological research on cave-type oil and gas reservoirs.

Due to the large burial depth of caved oil and gas reservoirs in the Tarim Basin, the seismic signal absorption and attenuation are severe, resulting in low original primary frequency of the target layer of seismic data. Conventional seismic attribute analysis techniques and frequency absorption and attenuation techniques are difficult to achieve satisfactory results. In the conventional frequency absorption and attenuation attributes, both oil-bearing beads and water-bearing beads show strong absorption and attenuation characteristics (Fig. 11, *a, b*). To address this problem, research work on the detection of oil-bearing gas properties in caves was conducted using the above-mentioned phase decomposition technique. The results show that the oil- and water-bearing caved targets can be accurately distinguished on the -90° phase dataset profile after phase decomposition (Fig. 11, *c*).

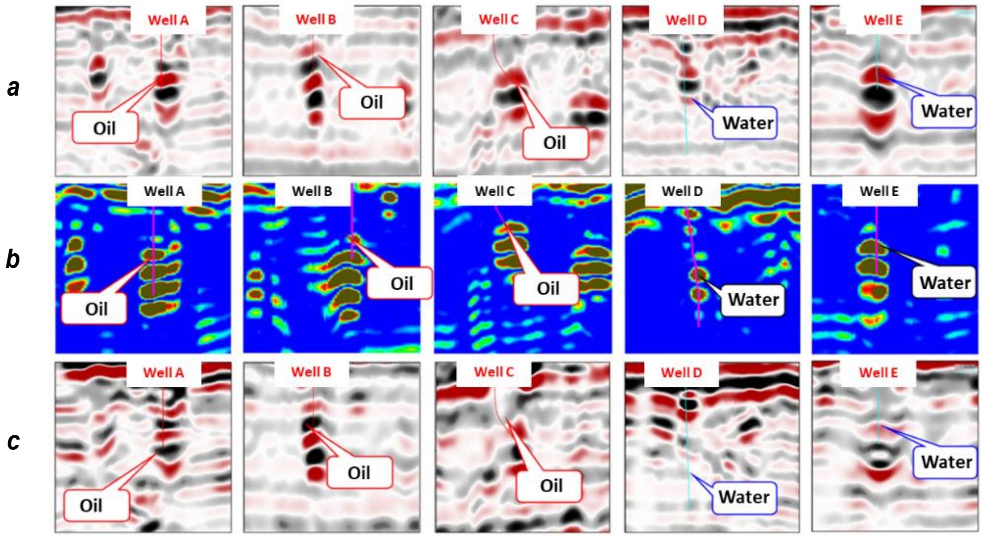

Fig. 11. Sections of raw seismic (top), frequency absorption decay (middle) and -90° phase component (bottom):
a – original seismic profile; b – frequency absorption attenuation profile; c – -90° phase component body comparison profile
Рис. 11. Участки исходных сейсмических данных (вверху), затухания частотного поглощения (в центре) и фазовой составляющей -90° (внизу):
a – исходный сейсмический профиль; b – частотный профиль затухания поглощения; c – профиль сравнения фазового компонента тела -90°

The reservoir of the Kepingtag Formation of the Silurian System in an area on the north slope of the Tarim Basin is a clastic reservoir with wide lateral variation in reservoir properties. In order to improve the development effect and optimize the development well deployment, the lateral variation of reservoir properties needs to be finely delineated. However, due to the large burial depth of the target layer, which is below 5,000 m on average, and the poor reservoir properties, thin thickness of the target layer, and small difference in wave impedance between the reservoir and non-reservoir, coupled with the low resolution of conventional seismic data, reliable reservoir prediction cannot be performed using conventional techniques. In response to the demand of development and production in this area, the spectrum recovery resolution enhancement technique was used for processing, and the resolution of the processed seismic data was significantly improved (Fig. 12). The overlay before and after resolution enhancement of seismic lines over SS9 well shows the profile (variable density is shown beforeprocessing, variable area is shown after processing, and well curve is GR), and the Paleozoic clastic reservoir can be clearly reflected at the target layer lateral variation.

It can be seen from the seismic profiles before and after improving the resolution of the main survey line over SS9 well: the geological features of reservoir thickness gradually thinning laterally are completely not reflected in the conventional seismic data, but are more clearly reflected in the high-resolution problem, and the seismic data have effectively improved the vertical and lateral resolution of the thin layer.

Fan delta identification in a North American block. The main producing layer of a North American block, the P formation, is a sedimentary unit compounded by multiple submerged fan deltas with complex reservoir lateral variations. Previous studies have confirmed that this reservoir is mainly a lithological reservoir controlled by lithological pinchout, and the reservoir is a fan delta sedimentary sand body. Several wells have been drilled in the main hydrocarbon-bearing objective, and although the wells drilled in different structural areas have similar trap conditions and have found reservoir sands, the hydrocarbon-bearing properties vary greatly. Some of the wells are highly productive, while others are mainly dry, resulting in a low drilling success rate. Previous research work has also been done, especially reservoir prediction studies using various seismic inversion techniques, hoping to accurately identify different reservoir units and predict the reservoir properties of different fan bodies, but all failed to solve the problem well.

Since different fans were formed at different times and under different depositional environ-

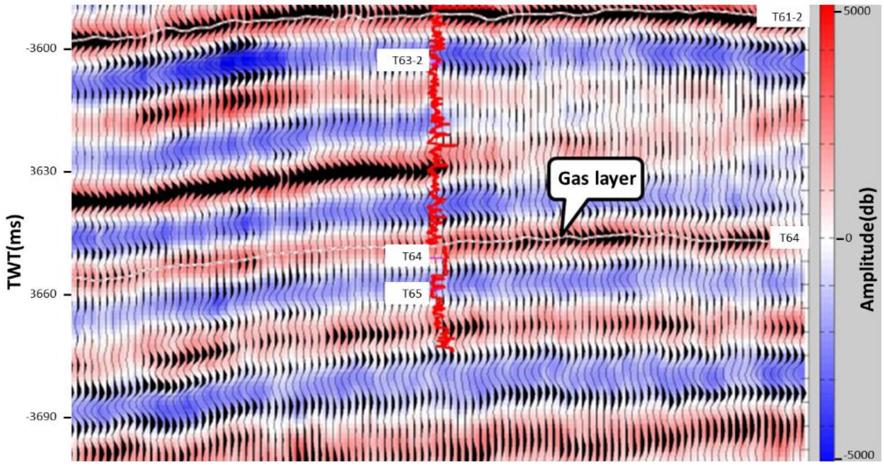

Fig. 12. Seismic sections of high-resolution processing (wiggle) overlay on raw (color)
Variable area is shown for conventional profiles, variable density is shown for profiles after resolution enhancement processing; well log is gamma-ray
Рис. 12. Сейсмические участки наложения обработанных с высоким разрешением данных синусоидные колебания) на необработанные (цветные)
Переменная площадь показана для обычных профилей, переменная плотность показана для профилей после улучшенной обработки с высоким разрешением; каротажная кривая дана в гамма-излучении

ments, their rock components, lithological assemblage characteristics, monolayer thickness, and sand-mud interstratification frequencies are different. And the frequency attributes in the seismic signal are most sensitive to this difference in response. Therefore, we can start from the frequency domain of the seismic signal to identify and classify different fans more accurately.

On the RMS amplitude map picked up along the top surface of the P-layer on the original full-band seismic data (Fig. 13, *a*), multiple strong amplitude zones representing sandstone development areas can be observed. In the strong amplitude zones, although the amplitude intensity varies, the overall distribution is contiguous, which is interpreted as a reservoir distribution feature with multiple stacked fans lateral distribution. However, this amplitude feature is difficult to distinguish different fans, and it is impossible to accurately identify the fans with favorable reservoir development and their boundaries. Using CLSSA high-resolution spectral decomposition technique, the original seismic data is decomposed into multiple single frequency datasets and the amplitude map is extracted separately for each single frequency. Different geological units can be clearly identified in the RMS amplitude maps of different single-frequency along the layers. In the 10 Hz single-frequency along-layer RMS amplitude map (Fig. 13, *b*) multiple submerged fans are identified separately and are more clearly shown. Rather, on the 20 Hz and 30 Hz single-frequency along-layer RMS amplitude maps (Fig. 13, *c, d*) the delta plain channel and delta plain deposits are more clearly reflected. This result improves a strong support for optimizing the well deployment plan and improving the drilling success rate.

Identification of gas-bearing properties of tight sandstone gas reservoirs in Ordos Basin. Ordos Basin is one of the important hydrocarbon-bearing basins in China, and the main reservoir is tight sandstone, which is difficult and risky to explore and develop. Due to the large variation of lateral properties, uneven gas abundance, and complex gas-water relationship, seismic data is needed to identify and predict productive areas to reasonably deploy development wells. However, due to the high hardness of the reservoir skeleton in the area and the weak difference in seismic response between the gas formation and the surrounding rocks, studies have been conducted several times using conventional oil and gas identification techniques, but the results are not obvious.

To accurately identify gas-productive areas, phase decomposition was applied. As shown in Figure 14, conventional seismic amplitudes did not distinguish gas from wet wells (Fig. 14, *a, b*), while amplitudes on the -90° phase component clearly do so (Fig. 14, *c, d*). These results were eventually verified from gas logging and actual well test results.

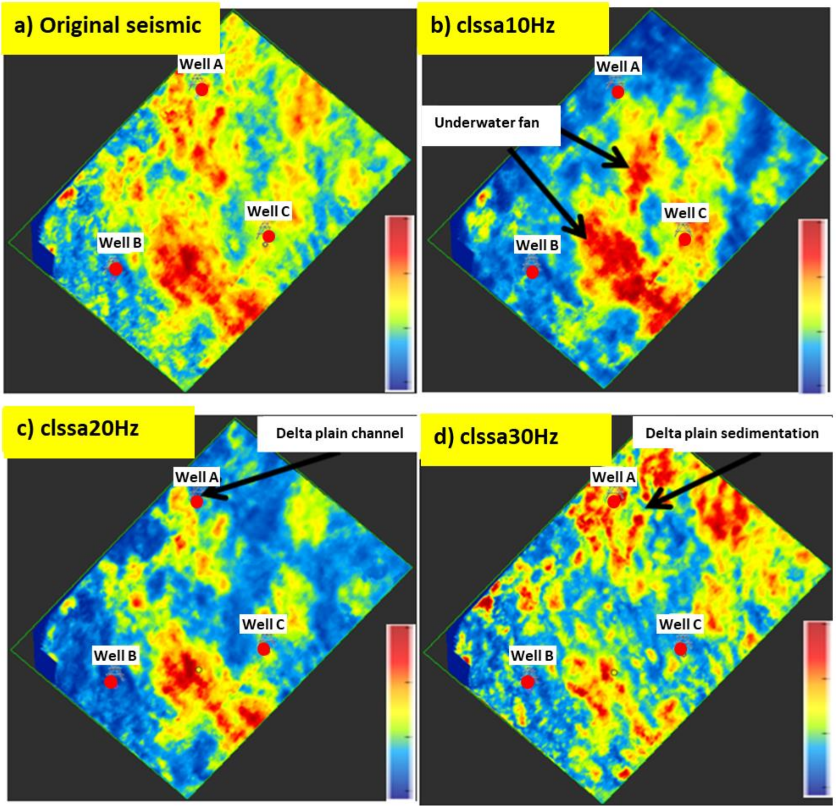

Fig. 13. Slices of root-mean-square amplitude on P layer in iso-frequency volumes
Рис. 13. Срезы среднеквадратичной амплитуды на слое P в изочастотных объемах

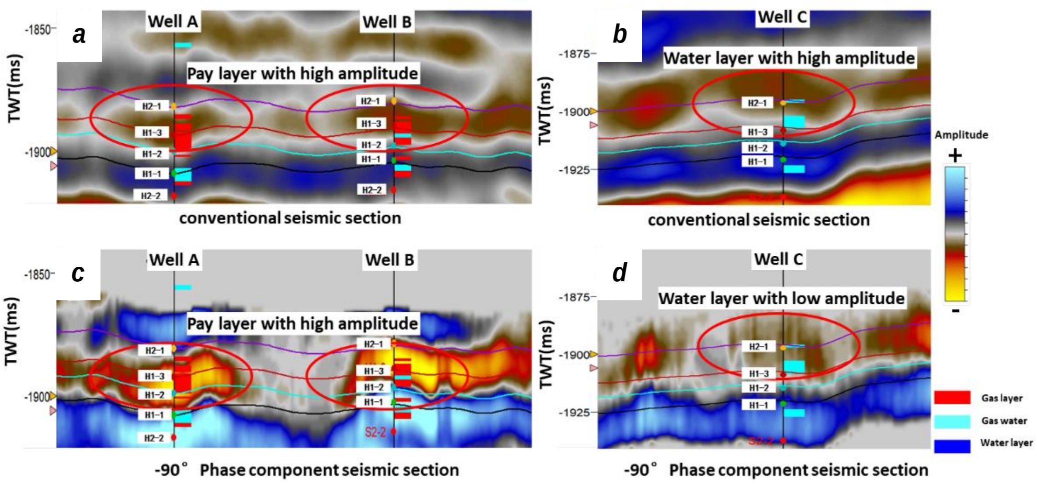

Fig. 14. Sections of raw seismic and -90° phase component:
a – over well A and B conventional seismic profile; b – over well C conventional seismic profile;
c – over well A and B -90° phase profile; d – over well C -90° phase profile
Рис. 14. Участки необработанных сейсмических данных и фазового компонента -90°:
a – условный сейсмический профиль по скважинам A и B; b –условный сейсмический профиль по скважине C;
c – фазовый профиль -90° по скважинам A и B; d – фазовый профиль -90° по скважине C

Bohai Bay faulted lacustrine shale oil prediction. Bohai Bay basin is a Cenozoic terrestrial faulted lacustrine basin developed in a regional extensional context, in which the shale oil exploration and development has achieved a major breakthrough with high and stable production from lacustrine shale for the first time in China. The studied area has 7 oil-rich layers, which can be further divided into 21 small layers with a single layer thickness of 10~30 m. Since horizontal well development requires a more accurate understanding of each oil-rich single layer, the existing seismic data resolution is difficult to achieve direct identification and interpretation of individual layers, which makes it difficult to trace the precise desired path of horizontal wells. Therefore, it is necessary to reasonably improve the resolution of seismic data, clarify the lithological sweet spot distribution, and ensure that the designed horizontal section passes through the sweet spot layer to achieve single well production enhancement and stable production.

According to the log characteristics of the shale oil reservoir, the sweet spot section of the target layer is mainly characterized by low impedance. The seismic data were processed with improved resolution by applying the spectrum recovery improved resolution technique, so that each oil-rich thin layer has a corresponding reflector. As shown by extracting the well-side seismic traces at well Z, the impedance prediction results from improved resolution processing correspond well with the logged reservoir, and the vertical and lateral impedance characteristics of the layer and the thickness variation of the individual layers can be clearly identified (Fig. 15).

Conclusion

Throughout the history of global reservoir exploration and development, every breakthrough and development is associated with the development and application of new technologies. Seismic data is one of the most important foundations in geological research of oil and gas exploration and development, and the development and breakthrough of seismic data processing technology will certainly greatly improve the success of oil and gas exploration and development.

Spectrum recovery high-resolution processing technology has dramatically improved the ability of seismic data to identify stratigraphic units, making it possible to directly identify and study individual reservoir layers. The multiscale fault detection technology (FaultDetect) makes some small faults and complex fault systems that are difficult to interpret more clearly reflected, and improves the reliability of structure interpretation. Spectral decomposition and phase decomposition techniques have improved the dimensionality of seismic attribute studies and brought new perspectives and means for reservoir studies and hydrocarbon properties prediction.

From several application examples mentioned above, it can be seen that the application of new technologies has further refined and rationalized the reservoir research based on seismic data. Whether it is for reservoir thickness below the tuning thickness, which cannot be identified and interpreted by conventional seismic methods, or for the fine description of complex

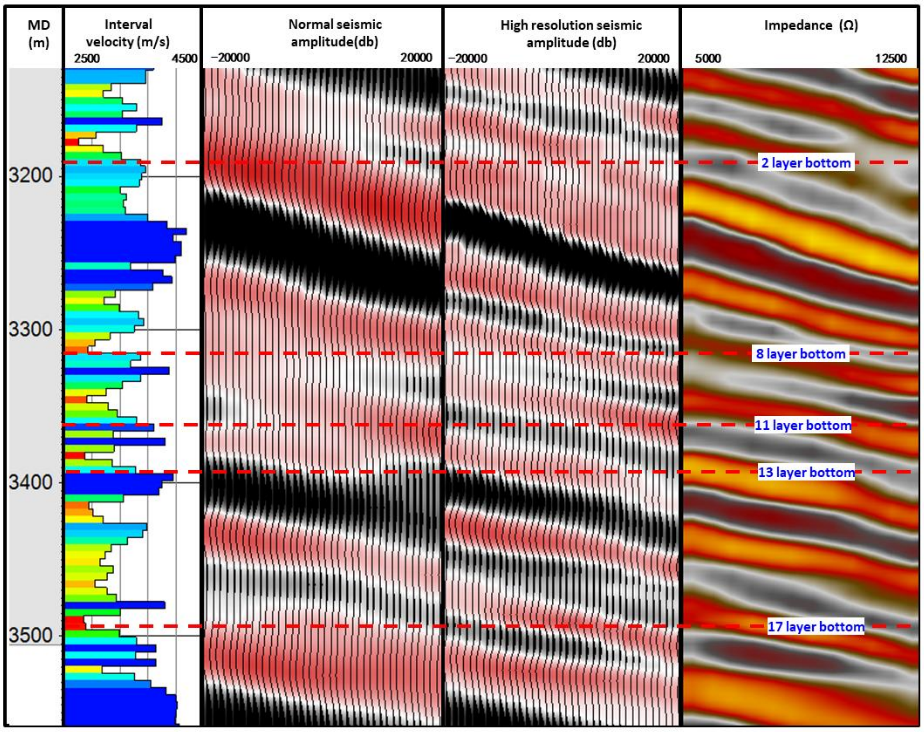

Fig. 15. Seismic sections before and after high-resolution processing
Рис. 15. Сейсмические участки до и после высокочастотной обработки

reservoirs, as well as a variety of geological and geophysical difficulties such as unconventional hydrocarbon enrichment segment carving, the use of high-resolution special processing technology and analysis from multiple dimensions of amplitude, frequency and phase will be a very cost-effective solution.

The quality of seismic data has a great influence on these methods, especially the signal-to-noise ratio and fidelity of seismic data. In the current conventional seismic processing work, some frequency lifting methods are often used to broaden the bandwidth of seismic data, but because these methods often have poor fidelity, the correspondence between seismic signals and subsurface geological units is changed and destroyed, which leads to unreasonable and reliable results when the new techniques in this paper are used for processing. Therefore, fidelity in conventional seismic processing should receive more attention.

The techniques presented in this paper have been successfully applied in many oil and gas regions around the world, and have helped to improve the exploration success rate and optimize the development plan. With the continuous development and promotion of these and other new technologies, it will effectively promote the oil and gas exploration and development work in the direction of more detailed, deeper and more efficient progress.

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Все авторы сделали эквивалентный вклад в подготовку публикации.

Conflict of interests / Конфликт интересов

The authors declare no conflicts of interests.
Авторы заявляют об отсутствии конфликта интересов.

The final manuscript has been read and approved by all the co-authors.
Все авторы прочитали и одобрили окончательный вариант рукописи.

Information about the article / Информация о статье

The article was submitted 05.09.2022; approved after reviewing 02.10.2022; accepted for publication 08.11.2022.
Статья поступила в редакцию 05.09.2022; одобрена после рецензирования 02.10.2022; принята к публикации 08.11.2022.